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Optimizing Physical Systems with Digital Twins

Integration, Challenges, and Applications

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Introduction

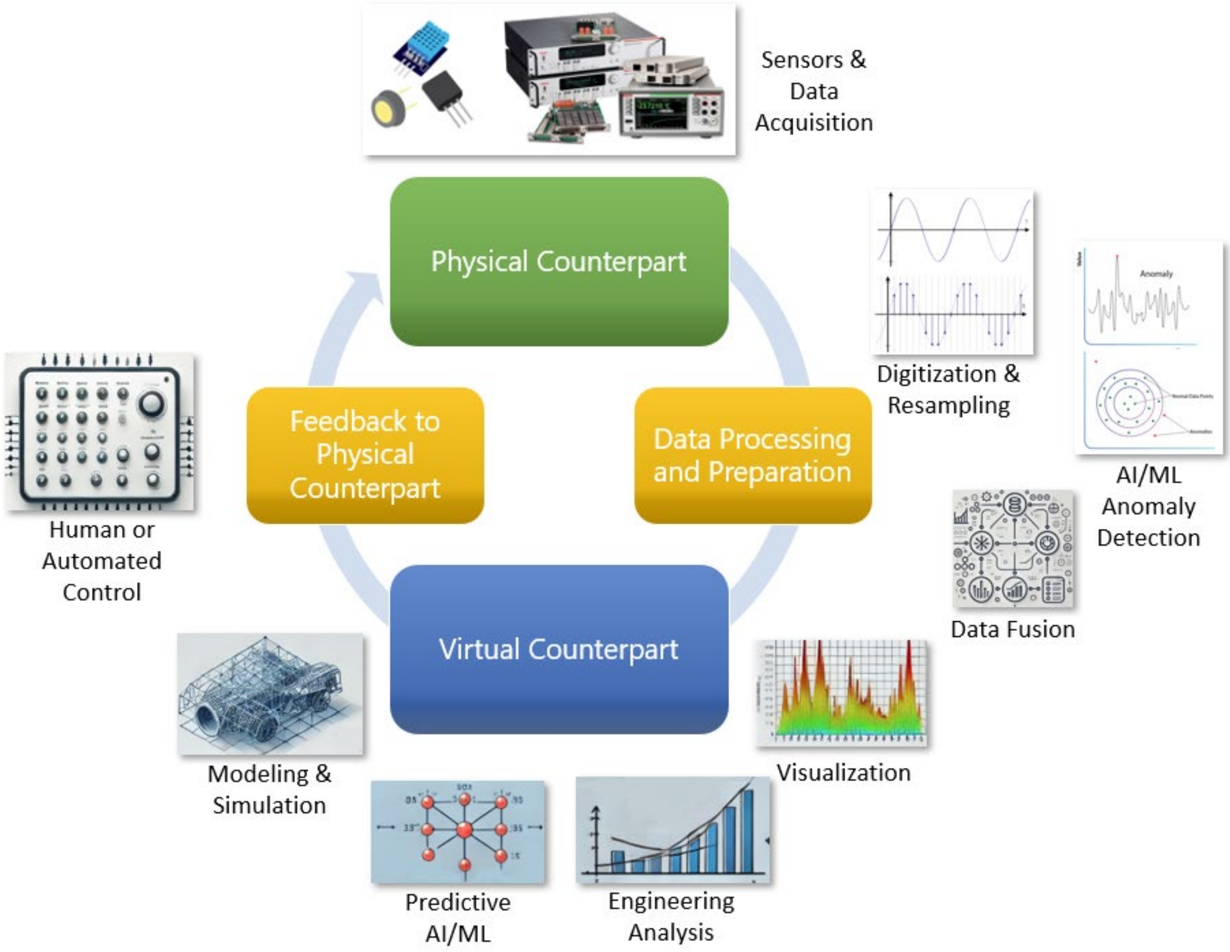
The Digital Twin concept entails developing an accurate virtual representation of a physical system or subsystem composed of hardware and software components. This duality in representations facilitates the seamless coordination and interaction between the physical and virtual entities. The following discussion clarifies the data flows and interactions between these counterparts, highlighting the processes involved in capturing, processing, and leveraging data to enable informed decision-making as well as the optimization and control of the physical system.

Any productive discussion on Digital Engineering requires a clearly defined lexicon describing the relevant terms. In our experience, the absence of such a lexicon often leads to program bottlenecks and failures. To address this, we have prepared the following hierarchical chart and an additional white paper that defines our Digital Engineering lexicon based on guidance from the Under Secretary of Defense on 21 December 2023 and details in reference [1]. Central to this discussion is the Digital Twin, whose definition in reference [1] is repeated below:

> *Digital Twin [DoDI 5000.97p]*
>
> *A computerized representation (integrated set of models) that serves as the real-time digital counterpart of a physical object or process. A digital twin is a virtual representation of a product, system, or process that uses the best available models, sensor information, data collected from the physical system, and input data to mirror and predict system activities and performance over the life of its corresponding physical twin and inform system design changes over time. There can be multiple digital twins of a system, but all digital twins should be based on authoritative sources of information and have clearly defined uses and scopes. Digital twins may vary in fidelity, based on the use case.*

Digital Twins and Hardware-In-The-Loop

Digital Twin technologies build upon traditional Real-Time Hardware-In-The-Loop (HWIL) Systems and, in the long term, offer a mechanism to improve a program's Return on Investment (ROI), while providing more flexibility to adapt to changing requirements and objectives. Digital Twins provide several benefits compared to conventional real-time HWIL systems, specifically in terms of flexibility, cost-effectiveness, predictive maintenance, data integration, remote accessibility, and scalability. Compared to HWIL settings, Digital Twins have the advantage of being more easily updated and adjusted for unexpected situations, allowing them to be more flexible in responding to changing program needs. This adaptability can result in significant cost reductions throughout the duration of extended projects. By incorporating sophisticated analytical tools and artificial intelligence/machine learning into a Digital Twin environment, it is possible to boost the capability to forecast and prevent failures, hence greatly streamlining and enhancing maintenance procedures. Furthermore, the collaborative characteristics of Digital Engineering tools in Digital Twins can enable effortless integration and analysis of diverse datasets. Accessing integrated data and test results remotely can be simplified, allowing for improved collaboration among teams that are spread out geographically. This capability is traditionally unavailable in HWIL systems. Ultimately, the adaptable structure of Digital Twins facilitates the effective interchange of process elements and instruments, enabling systems to expand in intricacy without sacrificing performance or manageability.



Digital Twin Counterparts and Information Flow

The Physical Counterpart

The Physical Counterpart of a Digital Twin is instrumented with various observation systems, including sensors and data acquisition systems, to monitor and capture real-time measurements continuously. The purpose of collecting sensor data is three-fold:

- **Real-Time Monitoring and Control:** Sensor data can be leveraged to continuously monitor the system's performance. By visualizing and analyzing this data, we can gain valuable insights on how to improve system performance. This analysis empowers us to develop control commands for the Physical Counterpart, fine-tuning the system performance and ensuring optimal functionality.

- **Development of Virtual Models:** The sensor data can be leveraged to develop a virtual representation of the Physical Counterpart, forming the foundation for digital models that accurately characterize the systems performance.
- **Verification and Validation (V&V) of the Virtual Models:** The sensor data can be leveraged for V&V of the Physical Counterpart by comparison of predictive data against measured system performance.

The acquisition systems collect and handle the raw data, ensuring its reliability and precision before sending it to the virtual component for additional analysis. Advanced data integration techniques can be employed to handle the large amount and intricate nature of the created data, facilitating seamless integration of the various data sources.

A unique aspect of the Physical Counterpart is the possibility of replacing it with another virtual model while developing a Digital Twin. This innovative approach allows us to emulate the interfaces and data flows necessary to complete the system. By embracing this non-traditional method, we can foster more flexibility and experimentation during the Digital Twin development process, ensuring that the final system is accurately represented and functions as intended.

Data Processing and Preparation

Once data is captured, it undergoes several processing layers to prepare it for use by the Virtual Counterpart. Sensor fusion techniques may combine data from multiple sensors, enhancing the quality and reliability of the measurements. Digital sampling and temporal resampling processes may be applied to prepare the data based on the needs of the Virtual Counterpart. A key part of this process involves the use of advanced AI and Machine Learning (AI/ML) algorithms. These algorithms play a crucial role in identifying patterns, anomalies, and insights within the data, ensuring that the data accuracy is maintained and is enriched with actionable intelligence. Data assimilation methods are then used to incorporate this processed data into the virtual model, ensuring that the virtual representation reflects the Physical Counterpart in real-time.

During the Physical Counterpart design phase, preliminary analysis data from the virtual model can be leveraged to refine and optimize the physical design. This iterative process replaces the virtual model with more accurate and detailed virtual representations as the design matures. This approach ensures that the data flows and interfaces are thoroughly validated, leading to a more robust and reliable final system. By continuously updating the virtual model with refined data, the Digital Twin remains an accurate and dynamic representation of the physical system throughout the development lifecycle.

The Virtual Counterpart

The Virtual Counterpart of a Digital Twin leverages advanced tools and techniques to simulate, analyze, and visualize the physical system. This process begins with tracing system requirements, which define the expected performance and functionalities of the physical system. A comprehensive functional architecture is developed from these requirements, outlining the system's various components and interactions. The Virtual Counterpart includes detailed simulations based on first-principle physical, mechanical, and empirical models, ensuring that every aspect of the physical system is accurately represented. These simulations allow for predictive analysis and scenario testing, providing insights into how the system will perform under various conditions and enabling continuous design refinement to meet evolving requirements. By maintaining a clear traceability path from requirements to functional architecture and ultimately to the detailed virtual model, the Digital Twin ensures that the physical system is developed and operated according to its intended specifications and performance goals.

The Virtual Counterpart may include:

- **Modeling and Simulation:** Creating detailed simulations based on first-principle physical, mechanical, and empirical models. These simulations allow for predictive analysis and scenario testing.
- **AI/ML Integration:** Employing AI and ML models to enhance predictive capabilities and provide deeper insights. These models continuously learn and adapt, improving their accuracy and effectiveness as they learn.
- **Analysis Tools:** Incorporating advanced analytical tools and techniques such as statistical analysis, performance analysis, finite element analysis (FEA), and computational fluid dynamics (CFD) to perform in-depth evaluations and optimizations of the system's performance under various conditions.
- **Visualization:** Visualization involves using advanced graphics and animation techniques to present data and simulation results intuitively and understandably. This visualization aids in understanding complex interactions and facilitates informed decision-making.

In addition to the above components, various engineering disciplines or functional ares such as the following can interact with the Digital Twin through the Virtual Counterpart, providing essential insights and improvements.:

- **Architecture Development**: Structuring and defining the overall system architecture, ensuring all components are coherently integrated.
- **Risk Management:** Identifying, assessing, and mitigating potential risks throughout the system's lifecycle.
- **Requirements and Verifications:** Ensuring that the system meets all specified requirements and that these requirements are verified through appropriate tests and analyses.
- **Software Assurance:** Ensuring the reliability and security of software components within the system.
- **Reliability, Availability, Maintainability, and Testability (RAMT):** Focusing on the system's reliability, ease of maintenance, and overall testability to ensure long-term operability.
- **Product Security Engineering:** Safeguarding the system against potential security threats and vulnerabilities.

- **System Testing:** Conducting comprehensive testing to validate system performance and functionality.
- **Obsolescence Management:** Addressing potential issues related to component obsolescence and ensuring the system remains up-to-date and functional throughout its lifecycle.

This comprehensive approach ensures that the Virtual Counterpart is a robust, reliable, and accurate representation of the Physical Counterpart, supporting informed decision-making and optimal performance. These engineering disciplines integrate seamlessly with the Digital Twin to analyze and optimize various system configurations. Simulating different scenarios and configurations helps the Virtual Counterpart identify the most efficient and effective solutions, ensuring the Physical Counterpart meets all performance and reliability requirements.

Validation of the Virtual Counterpart is essential to ensure its accuracy and reliability. Such validation involves rigorous testing and verification processes comparing virtual model outputs with system performance data. However, this validation becomes more challenging when the physical system does not yet exist. Researchers are exploring various methodologies to address this, such as:

- **Simulated Environments:** Creating detailed simulated environments that mimic real-world conditions to test virtual models.
- **Incremental Development:** Gradually developing and validating the virtual model parallel to the physical system's development.
- **Historical Data Utilization:** Leveraging historical data from similar systems to validate the Virtual Counterpart's predictive capabilities.
- **Cross-Disciplinary Collaboration:** Engaging experts from various engineering disciplines to review and refine virtual models continuously.

In addition to these methodologies, performing validation and verification (V&V) of the individual predictive components of the Virtual Counterpart is crucial. Each component within the virtual model, such as AI/ML algorithms, simulation models, and analytical tools, must be individually validated to ensure their accuracy and reliability. This process includes:

- **Component-Level Validation:** Ensuring each predictive component produces accurate and reliable outputs. This involves comparing the outputs with known benchmarks and test cases.
- **System-Level Verification:** Verifying that all components communicate and integrate correctly throughout the system lifecycle. Proper communication between components is essential for maintaining the overall integrity and performance of the Virtual Counterpart.
- **Continuous V&V:** Implementing ongoing V&V processes as the system evolves and new data becomes available. This ensures the Virtual Counterpart remains an accurate and dynamic representation of the physical system.

Despite these approaches, the field still requires substantial advancements to establish robust and universally accepted validation techniques for Digital Twins. Ensuring the Virtual Counterpart's fidelity and reliability remains critical for ongoing research and development in Digital Engineering.

Human-Digital Twin Interaction

The interaction between humans and the Digital Twin is a critical system component. The Virtual Counterpart provides a wealth of information humans use to make informed decisions. The Digital Twin's visualization and analysis capabilities support this human-in-the-loop decision-making process, enabling stakeholders to interpret data, evaluate scenarios, and make strategic decisions. Based on this information, control commands for the physical representation may be developed in preparation for feedback by a human or relegated to an autonomous control system.

Feedback From Virtual to Physical

Whether made by humans or automated systems, decisions (control commands) are communicated back to their Physical Counterparts. This feedback loop ensures that the physical system is continually optimized based on the insights and predictions derived from the virtual model. Automated control systems may directly implement these decisions to adjust operational parameters, enhancing the efficiency, performance, and reliability of the Physical Counterpart.

Digital Twin Examples

Several other excellent Digital Twin examples can be found in “Foundational Research Gaps and Future Directions for Digital Twins (2024)” [3]. Below we build on these examples, examining a potential Digital Twin of a Rocket Motor, illustrating how Virtual and Physical Counterparts can work together to optimize performance and maintenance.

A concept for a Digital Twin of a rocket motor would involve creating both a Virtual Counterpart and a Physical Counterpart that work together to optimize performance and maintenance. The Physical Counterpart, the actual rocket motor, could be equipped with numerous sensors designed to continuously monitor real-time parameters such as temperature, pressure, vibration, and fuel efficiency. This data would be collected and preprocessed to ensure its reliability and precision before being transmitted to the Virtual Counterpart.

The Virtual Counterpart, fueled by machine learning (ML) models trained on a vast database of sensor data and test logs from a fleet of rocket motors, could be a game-changer in predicting potential issues. It would include parameters representing each motor's operating conditions and the ML models' numerical model parameters. This Virtual Counterpart would simulate various operating scenarios to predict potential issues such as material degradation and suggest optimal maintenance schedules, showcasing its predictive capabilities and reassuring the audience of its potential.

Decision tasks facilitated by the potential Digital Twin could encompass a range of actions, from maintenance planning to real-time optimization. For instance, the Virtual Counterpart could provide computational estimates of possible material degradation, informing decisions on necessary maintenance and inspections. Human operators could execute these decisions automatically through the Digital Twin system.

Furthermore, the Digital Twin could be a game-changer in optimizing fuel efficiency in real-time, simulating emergency response scenarios for mission planning, predicting parts that may soon need replacement to streamline inventory management, and ensuring regulatory compliance with safety standards. It could also conduct cost-benefit analyses of various maintenance strategies, control noise and vibration levels, and assess plans for emission reduction. By integrating these decision-making capabilities, the Digital Twin could significantly enhance the operational efficiency, safety, and regulatory compliance of the rocket motor, providing comprehensive benefits that could revolutionize the industry.

Challenges in Digital Twin Implementations

Implementing Digital Twin technology presents several significant challenges that must be addressed to realize its full potential. These challenges include infrastructure development, obtaining useful data without physical hardware, validation and trust, up-front costs, and proving benefits.

- **Infrastructure Development:** Creating the necessary infrastructure to support Digital Twin technology is complex and resource intensive. This includes developing high-performance computing systems, robust data storage solutions, and secure communication networks. Additionally, integrating various software tools and platforms to ensure seamless data flow and interoperability between the virtual and Physical Counterparts requires significant technical expertise and investment.
- **Obtaining Useful Data in the Absence of Physical Hardware:** One of the critical challenges in Digital Twin development is obtaining useful data when the physical hardware still needs to be created. In such cases, developers must rely on simulated data, historical data from similar systems, or data from preliminary physical prototypes. Ensuring that this data is accurate, and representative of real-world conditions is crucial for developing a reliable virtual model. One novel method for achieving this is the use of Digital Surrogates[1], an area currently being pioneered by DESE Research, Inc.
- **Validation and Trust:** As previously discussed, establishing trust in the Digital Twin is a collaborative effort that requires rigorous validation and verification processes. This

includes validating individual predictive components, ensuring proper communication between components, and continuously updating the virtual model as new data becomes available. Building this trust is a gradual process that demands ongoing effort and collaboration among various stakeholders.

- **Up-Front Costs:** The initial costs of developing and implementing Digital Twin technology can be substantial. These costs include investments in infrastructure, software, data acquisition systems, and skilled personnel. While the long-term benefits of Digital Twins can outweigh these initial costs, organizations must carefully evaluate the financial feasibility and develop a clear roadmap to achieve a return on investment.
- **Proving Benefit:** Demonstrating the tangible benefits of Digital Twin technology to stakeholders is essential for gaining support and securing funding. This involves showcasing successful case studies and providing clear metrics on performance improvements, cost savings, and enhanced decision-making capabilities. Developing comprehensive pilot projects and conducting thorough cost-benefit analyses can help prove the value of Digital Twins.
- **Configuration Management:** CM in a Digital Twin is challenging due to the complexity and dynamic nature of the system. It involves integrating diverse data sources, managing large volumes and varieties of data, and maintaining real-time synchronization between the virtual and Physical Counterparts. The need for robust version control, tracking interdependencies, and integrating with legacy systems adds to the difficulty. Ensuring data security and access control, establishing data governance policies, and performing continuous validation and verification further complicate the process. Additionally, scalability issues arise as the system grows, requiring advanced tools and collaborative efforts to maintain configuration integrity.

Conclusion

In summary, the duality of representations in a Digital Twin system encompasses the continuous interaction and data exchange between the physical and Virtual Counterparts. This interaction is facilitated through robust data acquisition, integration, processing, and assimilation techniques. The Virtual Counterpart, equipped with advanced modeling, simulation, AI/ML, and visualization tools, provides a comprehensive human-Digital Twin interaction and decision-making platform. The feedback loop ensures the physical system operates optimally, driven by data-informed decisions and continuous monitoring. This synergy between the physical and virtual representations exemplifies the transformative potential of Digital Twin technology in modern engineering systems.

References

[1] "A DoD Centric Digital Engineering Lexicon", Paul Leopard, DESE Research, Inc. 7/16/2024

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[2] "DoD Instruction 5000.97 Digital Engineering", Heidi Shyu, Under Secretary of Defense for Research and Development, Office of the Under Secretary of Defense, December 21, 2023.

[3] "Foundational Research Gaps and Future Directions for Digital Twins (2024)", National Academies of Science, Engineering, and Medicine, ISBN 978-0-309-70042-9 | DOI 10.17226/26894.

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